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Contribution of seed coat properties to seed performance and quality

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Abstract
Seeds are fundamental units of plant reproduction, archetypally composed of an embryo, endosperm and a protective seed coat. The seed coat derived from the ovule's integuments, plays multi-layered roles in safeguarding the embryo, regulating germination and enhancing seed survival. It obliges as a physical barrier, controls water and gas exchange, intermediates environmental sensing and facilitates dispersal. It also subsidizes to chemical defense and dormancy regulation. Furthermore, seed coats influence human health by providing dietary fiber, antioxidants, phytosterols and essential minerals. However, despite these advantages, the seed coat can also act as a barrier to germination and seedling development. In certain crops, traits such as excessive hardness, impermeability and presence of germination inhibitors can hinder uniform emergence, reduce seed vigour and increase susceptibility to pathogens. These hindrances emphasize the dual role of the seed coat, both as a protector and a potential obstacle highlighting the importance of understanding its structural and chemical properties for effective crop improvement and seed technology applications.

Keywords: Seed coat, embryo protection, germination, dormancy, crop improvement, seed technology

Introduction
What is a seed?
A seed is the mature ovule that develops after fertilization. It typically consists of three primary components: the embryo, endosperm (present or absent depending on the species), and seed coat. Seed development is a defining feature of higher plants (gymnosperms and angiosperms), distinguishing them from lower plants such as pteridophytes, which do not produce seeds. In gymnosperms, seeds are formed without an ovary and are therefore referred to as naked seeds. In contrast, angiosperms produce seeds enclosed within fruits, formed from the ovary, and are typically equipped with protective structures including the seed coat, food reserves (e.g., endosperm or perisperm), and a well-developed embryo.

Seed coat: structure and formation
The seed coat is the outermost protective layer that surrounds the seed and develops from the integuments of the ovule after fertilization. It plays a crucial role in safeguarding the embryo and regulating its interaction with the environment. A small opening called the micropyle is often retained in the seed coat, allowing water and gases to pass through during germination. The seed coat generally comprises two main layers:

Testa: The tough, thick outer layer derived from the outer integument, providing mechanical strength and protection.

Tegmen: The thin, delicate inner layer derived from the inner integument, assisting in internal protection and permeability control (Matilla *et al.* 2019) [8].

Multifunctional roles of the seed coat in seed quality and survival
The seed coat performs a variety of critical functions, contributing to seed quality, germination success, and seedling establishment. Its roles can be categorized as follows:

1. Dispersal mechanism
Seed coats often exhibit structural adaptations such as wings, hooks, hairs, or buoyant tissues, facilitating seed dispersal by wind, water, animals, or mechanical forces. These adaptations enhance the spatial distribution and survival chances of the species (*e.g*., tomato, lupins, maple, milkweed seed).

2. Hydration protection
The seed coat acts as a regulatory barrier, controlling the rate and extent of water uptake. This prevents osmotic shock or mechanical damage to the embryo during imbibition, particularly under fluctuating moisture conditions (*e.g*., lotus plant).

3. Physical support
As the seed germinates, the seed coat offers mechanical support to the emerging radicle and plumule, shielding them from soil particles, water pressure, and mechanical disturbance (*e.g*., beans).

4. Environmental sensing
The seed coat functions as a sensor, detecting cues such as light, temperature, moisture, and chemical signals, thereby determining the most favorable conditions for germination and dormancy release (*e.g*., oak trees).

5. Allelopathy
Certain seed coats release allelopathic compounds—bioactive chemicals that suppress the germination or growth of nearby competing plants. This chemical interference reduces interspecific competition and enhances seedling survival (*e.g*., black mustard).

6. Reserve mobilization control
During germination, the seed coat modulates the movement of enzymes and nutrients from storage tissues (like endosperm or cotyledons) to the growing embryo. This selective permeability ensures a controlled, efficient nutrient supply (*e.g*., quinoa).

7. Symbiotic relationships
In some species, seed coats facilitate associations with beneficial microbes, such as nitrogen-fixing bacteria or mycorrhizal fungi, aiding early nutrient acquisition and promoting healthy seedling growth (*e.g*., soybean) (Naflath *et al.* 2023) [9].

8. Physical dormancy
In species like lodgepole pine, the seed coat imposes physical dormancy, requiring specific environmental triggers such as freezing temperatures or fire to break dormancy. This ensures germination occurs under optimal ecological conditions (*e.g*., lodgepole pine).

9. Chemical defense
Seed coats are rich in secondary metabolites such as phenolics, flavonoids, and alkaloids that provide chemical defense against herbivores, pathogens, and seed predators (*e.g*., walnut).

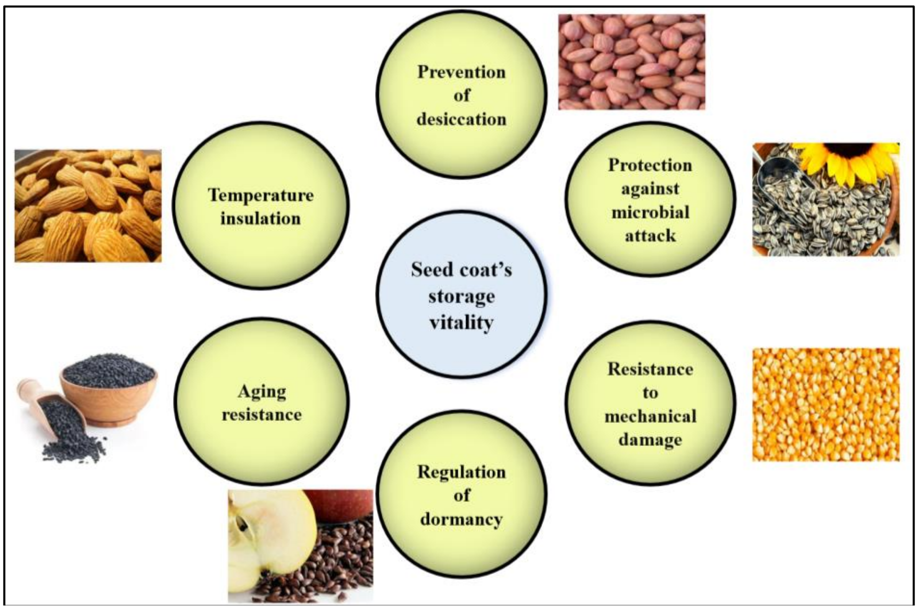
10. Water regulation
Specialized structures like micropyles or impermeable layers help control water absorption during seed imbibition, minimizing premature germination and improving seed longevity during storage (*e.g*., *Acacia victoriae*) (Julia *et al.* 2020) [5].

11. Nutrient storage
In some species, the seed coat serves as a nutrient reservoir, storing carbohydrates, lipids, proteins and minerals which supplement the embryo's requirements during germination (*e.g*., *Pisum sativum*).

12. Physical protection
The seed coat offers mechanical protection against external threats such as abrasion, microbial attack, insect predation, and environmental stress, acting as the first line of defense for the developing embryo (*e.g*., maize).

13. Regulation of germination
By acting as a barrier to water, oxygen, and light, and through the presence of chemical inhibitors, the seed coat regulates timing and conditions of germination, preventing premature germination under suboptimal conditions (*e.g*., chick pea).

Roles of seed coat during storage condition



During storage, the seed coat plays a crucial role in maintaining seed viability and quality by providing multiple protective functions (Durgbanshi *et al.* 2005) [3]. In groundnut, the seed coat prevents desiccation, preserving internal moisture and reducing the risk of loss in seed vigour. In sunflower, it offers a physical barrier against microbial invasion. The maize seed coat resists mechanical damage that may occur during handling or storage, safeguarding the embryo (Kozaki *et al.* 2022) [6]. In apple seeds, it helps regulate dormancy, ensuring seeds do not germinate prematurely under fluctuating storage conditions. The seed coat of black sesame contributes to aging resistance by slowing oxidative deterioration and preserving cellular integrity over time. Additionally, in almond, the seed coat provides thermal insulation, protecting the seed from temperature extremes and maintaining stable internal conditions, which are essential for long-term storage (Radchuk *et al.* 2011) [10].

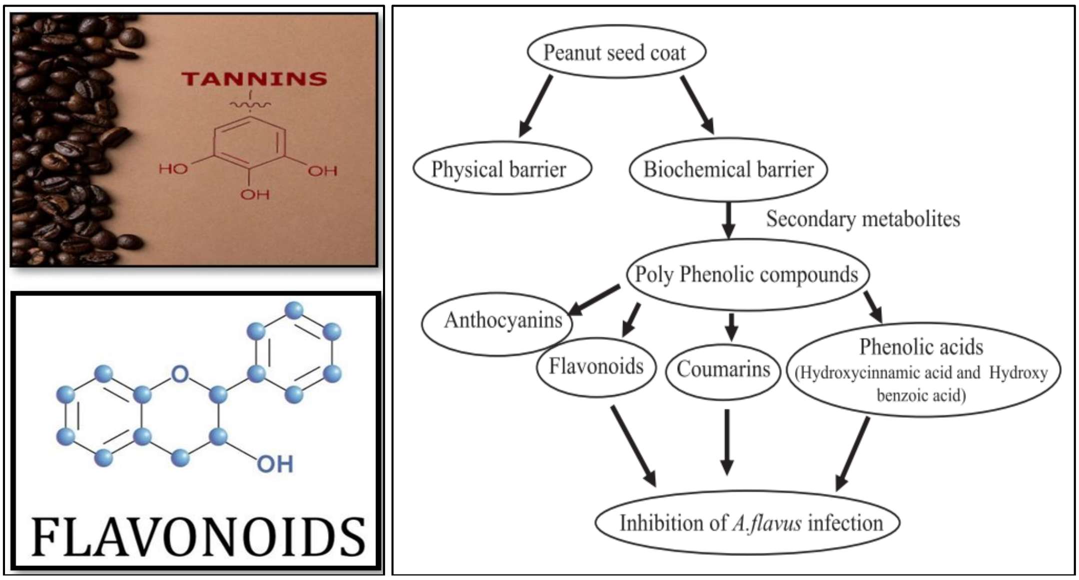
Factors influencing the functions of seed coat

Physical factors

- **Seed size:** Affects dispersal efficiency and seed coat surface area.
- **Seed texture:** Influences interaction with water, soil and dispersal agents.
- **Seed hardness:** Enhances protection against mechanical damage and predators.
- **Seed coat thickness:** Regulates permeability to water provides physical defense.
- **Seed coat colour:** Associated with light absorption, UV protection and pest deterrence.

Sr. No.	Legume	Seed coat colour	Agronomical effect
1	Winged bean	Brown	Enhanced nodulation and nitrogen fixation
2	Common bean	Light red	Disease resistance and symbiotic nitrogen fixation
3	Soybean	Black and brown	Enhanced antioxidant activities and anthocyanins
4	Azuki Bean	Black	Higher accumulation of anthocyanins
5	Peanut	Dark red	Higher polyphenol content (Ibrahim *et al.* 2011) [4]

Chemical factors



- **Lignin:** Increases rigidity and impenetrability of the seed coat.
- **Tannins:** Provide antimicrobial activity and deter herbivory.
- **Pro-anthocyanidins:** Contribute to pigmentation and protect against oxidative stress.
- **Flavonoids:** Act as antioxidants and chemical barriers against pathogens.
- **Chitinases:** Enhancing defense against microbial attack

Roles of seed coat in human health

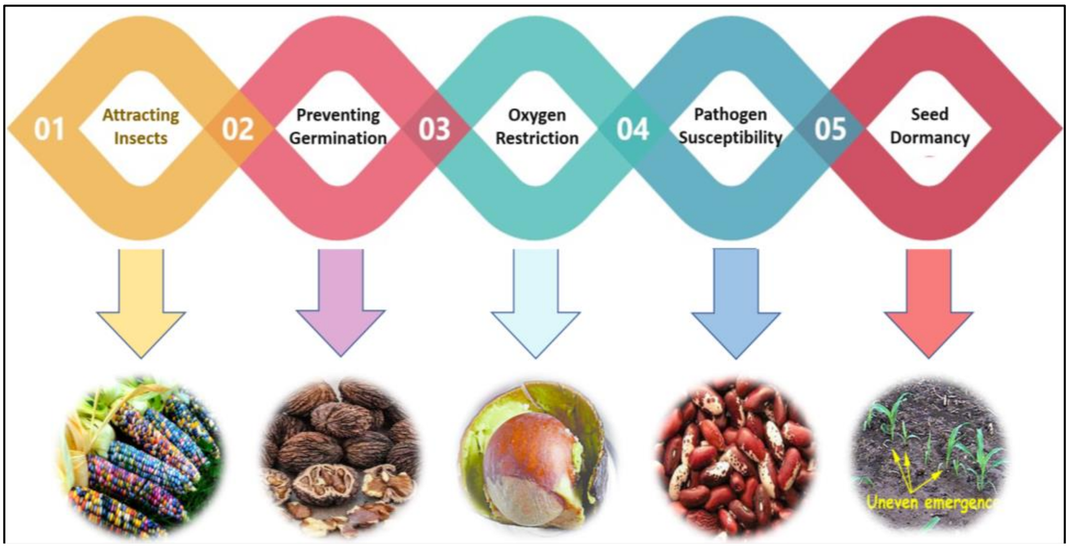
- **Promotes digestion:** Rich in dietary fiber, aiding bowel movement and preventing constipation (*e.g.*, Pumpkin).
- **Regulates blood sugar:** Soluble fiber slows glucose absorption, supporting glycemic control (*e.g.*, Barley).
- **Lowers cholesterol:** Contains phytosterols that reduce LDL cholesterol and heart disease risk (*e.g.*, Sunflower, Almonds) (Zoe *et al.* 2024) [11].
- **Provides antioxidants:** Flavonoids and phenolic compounds help reduce inflammation and oxidative stress (*e.g.*, Cacao beans) (Ali *et al.* 2022) [1].
- **Supplies essential minerals:** High in zinc, magnesium, and others crucial for metabolic functions (*e.g.*, Sesame).
- **Supports heart health:** Rich in omega-3 fatty acids and healthy fats that improve lipid profile and reduce inflammation (*e.g.*, Walnut).

Table 1: Macronutrient composition (%) of pulse seed coats

PSCs	Starch	Protein	Lipid	TDF	Ash	TPC
Mung bean	4.78	8.55-10.6	0.28-0.64	78.6	2.24-3.00	7.02-12.96
Azuki bean	-	6.1-6.5	0.9-1.1	73.3-80	1.9-3.0	54.45
Common bean	-	4.9-5.6	0.4-0.5	72-81	2.5-3.1	0.35-3.89
Broad bean	0.9	5.0-13.81	0.2-0.92	57.46-82	4.4-8.87	14.24-37.54
Pea	0.16-1.8	4.5	0.28	74.57	2.23	2.78-46.56
Chick pea	0.2-0.5	7.3	1.6	81.0-91.5	2.6	2.00-7.94
Lupin	-	3-6.6	1.5	79.84-86.59	2-3	0.68-1.28
Lentil	<10	8.58-8.64	0.18-0.91	71.32-73.34	2.11-2.23	67.82-87.61

Dark side of seed coat: hindrances and hazards

The seed coat essential for protecting the embryo. It can also present several hindrances and hazards that affect seed performance and plant development. In certain crops like maize, the seed coat colour plays a role in attracting insects, making the seeds more vulnerable to pest damage. In walnuts, the seed coat contains chemical inhibitors that prevent premature germination, which, although protective, can delay desired sprouting (Dave *et al.* 2011) [2]. Avocado seeds often face oxygen restriction due to the thick seed coat, hindering respiration and germination. In legumes like rajma (kidney beans), the seed coat may increase susceptibility to pathogens by trapping moisture or creating entry points for fungal infections (Leslie *et al.* 2021) [7]. Furthermore, in crops such as wheat, a hard or uneven seed coat contributes to seed dormancy and results in uneven emergence in the field. These examples illustrate the "dark side" of the seed coat, while it plays protective and regulatory roles, it can also hinder seedling vigour, uniformity, and health under certain conditions.



Conclusions

The seed coat is essential for seed protection, germination control and environmental interaction. Its many uses include microbial relationships, nutrition storage, physical defense and dormancy management. The seed coat can be advantageous in many ways but it can also present problems including oxygen limitation, delayed germination and heightened vulnerability to diseases or pests. While optimizing its protective advantages, targeted breeding and seed treatment techniques can help minimize its drawbacks.

Future Thrust

- Research should focus on understanding and utilizing seed-coat-mediated disease resistance and toxin reduction
- Utilizing seed coat's protective role may help to develop pest and disease resistant crop varieties which could be a way for sustainable farming
- Investigating the seed coat's impact on seed nutrition may aid in breeding crops with enhanced nutritional value to tackle global malnutrition
- Enhancing seed longevity by incorporating genetic insights through targeted breeding with identified QTLs
- Scrutinizes seed coat genetics and breeders optimize traits like thickness, permeability and composition using advanced techniques helps in enhancing crop performance, food quality and meet the evolving needs of farmers and consumers

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